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# COMPUTER MEASUREMENT OF BIOLOGICAL SOUND-SOURCE LOCATIONS FROM FOUR-HYDROPHONE ARRAY DATA

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TECHNICAL REPORT

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COMPUTER MEASUREMENT OF BIOLOGICAL SOUND-SOURCE LOCATIONS FROM FOUR-HYDROPHONE ARRAY DATA


Abstract

The measurement of sound arrival-times at the hydrophones of a three-dimensional array has been the difficult part of the analysis for biological acoustic source location. The development of a system that relegates these signal comparisons and measurements to computer analysis is described. The essential steps which require human judgment are retained allowing a flexible analytic procedure that requires less time, has greater accuracy, and less operator bias than manual measurements.

Introduction

One of the most vexing problems in underwater bioacoustic studies has been that of locating the source of sounds. Aquatic sound-makers are hard to find underwater and, even when they are at the surface, they are not readily identifiable; unlike most animals living in air, aquatic animals do not open their mouths to phonate.

We approached this problem with the development of a four-hydrophone three-dimensional array to attempt acoustic location of sound sources. Since the array was to be used at sea from small ships, a flexible non-rigid arrangement was preferred, and, to keep track of its varying dimensions, a system of concurrent calibration was utilized (Watkins and Schevill, 1971, 1972). For acoustic locations by means of this array, sound arrival-times at each hydrophone were measured and compared. The calibration system for determining the location of the hydrophones also used time measurements of sound arrival from two underwater sound sources (usually pingers). These time-differences were used to calculate relative hydrophone positions and then the locations in three dimensions of aquatic sound producers could be computed in relation to the array.

Experimentation established that a practical limit in the maximum dimensions of such a hydrophone array that could be used at sea was the overall length of the ship (Watkins and Schevill, 1972). The minimum size of the array depended on the potential resolution of the sounds during reception, recording, and analysis. With the usual animal pulsed sounds and approximately equal separations between all hydrophones, the minimum

array dimension was about 30 m, when sounds could be resolved to 0.01 msec.

Calculation of acoustic locations for the hydrophones in the array as well as the location for each sound source requires meticulous comparison of the sound and measurement of arrival-times at each of the hydrophones. A detailed study of the effect of error in these measurements during both calibration and location procedures emphasized the requirements for accuracy and consistency (Watkins and Schevill, 1972). As a result of these studies, refinements in the measurement procedures have evolved, and with this effort toward greater accuracy has come a marked reduction in the scatter of the location measurements. See, for example, Watkins and Schevill, 1974. The ideal system, of course, would be one that could take the sounds as they are received and translate them immediately into a three-dimensional source location. Though, for these animal sounds, such a system appears to be beyond the current "state of the art," we describe here the progress that has been made in this direction.

## Sound arrival time analysis

Measurement and comparison of sound arrival-times has utilized graphic representations of the analog data, including multichannel pen recorders and other graphic marking devices as well as oscillographic presentations. Generally, the paper marking devices have had too slow a response and could only be used for an indication of relative arrival-times and gross measurements. Oscilloscopes were more rapid, but difficult to read. More precise hand measurements were possible with plotted printouts

of multichannel digitized data.

In all of these direct measurement methods, the major difficulties proved to be those of finding the same parts of a sound to be compared. The traces of the same sound on different channels often appeared to be very different. Destructive and constructive interferences, as well as multipath effects of the environment, modified the representations of the sound so that identical features on the traces could not be identified for comparison. Examples of more extreme cases of this are illustrated by Watkins and Schevill, 1972. It became evident, therefore, that a comparison of the sound as a whole was necessary for consistent results.

One method for measuring time-differences between signals received on different hydrophone channels also permitted a comparison of the amplitude/time parameters of a pulse. This analysis (described by Watkins and Schevill, 1972) used superimposed oscilloscope traces and measurement of the delay between traces. However, these measurements and comparisons proved to be susceptible to operator bias and equipment drift.

Since the computations for location of the hydrophones in the array and the location of sound sources were habitually solved by computer, it seemed that the computer could also be utilized in comparison of the signals on different channels and the measurement of time differences between signals. In fact, it seemed that the whole location process perhaps could be accomplished automatically by computer. Why not, we reasoned, present the analog field data to the computer and program it to find the animal sounds, measure the time differences, and calculate the three-dimensional location of

the animals? Though this all appears to be feasible, we have been unable to accomplish the first condition of this set, i.e., computer recognition of the animal sounds.

Recognition of animal sounds

Underwater animal sounds of interest and for which locations are desired may not be the loudest sounds in the ambient noise. Instead, they may be masked by other sounds, and have few frequency components that are different from the background (which can be composed mostly of other sounds produced by the same kinds of animals). Successive sounds may vary in amplitude and sound spectra, and they may be repeated at irregular, sometimes apparently random, intervals. All this has frustrated attempts to achieve computer recognition of the animal sounds that need to be processed, though these sounds can be readily identified by the human ear.

A compromise in procedures has resulted from the experiments in computer recognition and time difference analyses. This is a sequence of analytical steps that lets the investigator designate the signals to be considered and specify the parameters for analysis, but relegates to the computer all of the signal comparison and time measurement routines, as well as the location calculations. Though this is far from the ideal of complete "automatic" analysis, it does reduce the time required for analysis and the potential of operator bias, and it gives repeatable highly accurate results.

The analysis that we describe depends, of course, on the facilities available for our use. Another computer system probably would change the

procedures, the details of analysis, and the time required for handling the data. However, the analytic steps ought to be adaptible to other systems.

Description of the analysis

The sounds from the four-hydrophone array are recorded on separate channels of magnetic tape in analog form, and include pulses from the calibration pingers as well as underwater animal sounds. Relative hydrophone positions and then the location of the underwater sound sources, both may be calculated from arrival-time-differences of the sounds received on the hydrophones. Analysis of these signals is performed on the Xerox Sigma 7 computer at the Woods Hole Oceanographic Institution, and the programs that are used were developed with the help of the WHOI Information Processing Center. The location program and computations were arranged by Donna Ekstrand and Mary Hunt (see Appendix to Watkins and Schevill, 1971); the analogue to digital program and the time-series analysis were arranged by Mary Hunt; multichannel plotting, threshold analysis, and data handling programs were written by Roger Goldsmith.

In brief, a three-dimensional location of an animal sound recorded by the four-hydrophone array may be found by plotting the signal, and selecting the specific portions of the plot to be examined in detail. Then these portions are filtered, signal thresholds located, spectral analysis and power spectra computed, and the signal components are cross-correlated. The sound arrival-time differences are used to calculate the locations.

A complete analysis requires the following steps:

1. Selection of the appropriate signals on the field tape to be analyzed, including the two calibration signals and the animal sounds.
2. Analog-to-digital conversion of the selected data.
3. Parts of the digital tape are manually chosed for plotting by selecting appropriate time periods.
4. Plotting of the digitized data to relate the signal sequences and sort out signal from noise.
5. The sounds are manually located on the plot and the indicated times are used to designate the portions to be analyzed.
6. These portions are converted to data files that are compatible with the analytic process. Several of these files can be stored on tape, or single data files may be used for direct processing.
7. Appropriate data files are designated for processing and analysis parameters selected.
8. The data files are filtered to reduce competing noise.
9. The relative time of the beginning (threshold) of the sound is located within the file on each channel.
10. A segment of sound around each of these threshold points is designated for detailed analysis.
11. The four segments of sound are analyzed by means of Fourier transforms.
12. Power spectra are calculated for each of the segments.
13. Cross-correlation functions are computed between pairs of the spectral estimates for these segments.
14. The lag times derived from the cross-correlations for the sound segments

are added to the threshold times to give relative time-differences for the sound arrival on each channel.

15. The calibration and sound source arrival-time-differences are arranged in proper order for the location computations.

16. The arrival-time-differences are used to compute the location of each hydrophone from the pinger pulses, and from the animal sounds a location for the source.

These steps are listed in Table 1 along with other pertinent components of the analysis.

The selection of only particular sections of the field recordings for analysis (step 1) reduces the length of sound sequences that have to be considered by the computer, thus saving in the cost of analysis. Sometimes re-recording selections from the field tape, or editing out unnecessary sequences, allows analysis of only the pertinent portions of sound. But this has to be balanced against the necessity of preserving the continuity of sound sequences, as well as their relative proximity in time to calibration pulses on the field tapes. Since there is always some motion in a non-rigid array, the signals to be analyzed provide more accurate locations when they are received within a short time of calibration signals. Each location, of course, is based on the relative hydrophone positions derived fr a calibration sequence.

The analog recording (step 2) is converted to digital time-series data at a rate that will reproduce the important parts of the signal. For a 12-kHz signal bandwidth, the four-channel analog tape may be played at $\frac{1}{2}$ speed and

digitization performed at a rate of 25 kHz (6250 Hz per channel). This rate is slow enough to permit the digitized data to be written almost directly onto magnetic tape. This avoids the use of secondary storage in the computer, and, in the WHOI arrangement, allows a much longer continuous time series to be recorded. (See program ADWW by Mary Hunt, WHOI Information Processing Center.)

Often it is advantageous to filter out noise backgrounds before the digital tape is made. Further and more specific filtering may be used later in the analysis, but, to reduce computer time, it is helpful to digitize as uncluttered a set of data as possible.

The digital data now may be plotted so that exact time relationships can be established and so that signals of interest may be examined in detail and selected for analysis. The digital time series data is scaled and plotted (step 4) as a series of individual points for each of the four channels (100 data points per inch) on an electrostatic plotter. (See program PLT4SIGNL by Roger Goldsmith, WHOI Information Processing Center.) The storage requirements of the WHOI system limit the plotting to samples of about 6 seconds of data per plot, but because of the accurate time relationships, sequential plots may be used for longer sequences. It takes about five minutes of computer time with this system to plot five seconds of four-channel data (digitized at a rate of 25 kHz).

If only a few locations are desired, individual signals may be selected to be analyzed directly, omitting steps 6 and 7. Direct analysis requires 2-3 minutes more computer time for each location than when a number

of signals are analyzed together (about 5 minutes versus 2 minutes per location). For the analysis, small bands of data points are selected around individual signal traces (step 5). A center time for this band and enough points to include the signals on all four channels are specified for each sound. By restricting the size of individual bands to be analyzed, much noise can be eliminated, and there is a considerable saving in computer time during the various steps of analysis. Multiple signal bands are most conveniently handled when stored as files on tape (step 6) to permit repeated analysis without returning each time to the digitized data. The signal files are stored in a form that is suitable for input to the time series analysis. (See program WHALSIG by Roger Goldsmith, WHOI Information Processing Center.)

The signal files of the four-channel data provide a convenient way to handle pertinent sounds for analysis. The duration of each file is short enough for relatively rapid processing in sequential analyses, and the signals are isolated from other confusing noises. Yet their relationship to the ambient sound is fixed by time; the files are keyed by time on the plot of the digitized data. They may be selected repeatedly for analysis and arranged in any desired sequence (step 7).

The analytical processes utilized to establish the signal relationships are handled together (steps 8 through 14) as one step, but actually are sequential. First, the file of data points surrounding the signals on all four channels may be filtered (step 8) to reduce further any competing noise. A variety of filters is available and the parameters for each may be specified

(see program TIMSAN (NUFILT) by Mary Hunt, WHOI Information Processing Center). In most cases a high-pass or band-pass filter is sufficient to assure favorable signal-to-noise ratios.

The signals are located by searching within each band for the first excursion of the sound that exceeds a threshold level (step 9). This is performed on all channels and detects the general sound arrival-time-relationships. Levels for the threshold analysis may be specified (see program THRESHOLD by Roger Goldsmith, WHOI Information Processing Center). The signal threshold times (relative arrival times) on each channel are indicated, then smaller segments of sound around the detected thresholds are designated for further analysis (step 10). The size of these segments and their proportions around the signal may be specified.

Each of the segments of sound that were selected are analyzed (step 11) by means of a "fast Fourier transform". A number of options may be specified to vary this analysis. The Fourier coefficients for the four channels are used, then, to compute their power spectra (step 12). They are processed in pairs, each channel being paired with every other channel. (See TIMSAN programs COEFF and FFAUSP by Kay Paine and Mary Hunt, and CCOR by Mary Hunt, WHOI Information Processing Center.) The cross--correlation function between signals on different channels is then computed (step 13) using the pairs of spectral estimates.

The cross-correlation functions that have been computed produce a refinement of signal location within the short sound segment analyzed for each channel. The resulting lag times are added (step 14) to the threshold

sound arrival-times to produce adjusted times for the four signals. (See program LOCPREF by Roger Goldsmith, WHOI Information Processing Center.) Differences in sound arrival-times then are arranged to conform to the input required for the calibration and location computations.

The output for each sound from this four-channel analysis is in the form of a computer card punched with the specified arrival-time differences. The analysis procedure (steps 8 through 14) requires approximately one minute per signal file on the WHOI system. The card output permits flexibility in the computation of locations for the sounds by permitting them to be arranged in any desired order (step 15). The sporadic nature of the calibration sequences in the field recordings often means that the sounds of interest occur some time later than or before a calibration; therefore interpolation between calibration sequences usually is required for accuracy.

The location program (step 16) and the geometry of the three-dimensional array was described by Watkins and Schevill, 1971, with appendix of program WHALOC by Donna Ekstrand and Mary Hunt. The time differences specified for the calibrations and other sounds are used to compute three-dimensional locations for the hydrophones in the array, and then for the sound sources. The program is very fast, using only a few seconds for each location. Consequently, it is feasible to return to steps 15 and 16 for other location computations using a variety of hydrophone positions (to ascertain, for example, the drift of the array).

The time required for a complete analysis for source location is long enough so that only potentially interesting sequences are analyzed. The

manual steps required are steps 1, 3, 5, 7, and 15. These permit the selection of appropriate sequences and manipulation of the parameters for analysis. The ability to adjust for variables maintains an important flexibility in the whole process. If a number of sounds are to be analyzed in the same way, however, the manual steps can be shortened to that of feeding program instructions to the computer. The computer is used in steps 2, 4, 6, 8 through 14, and 16.

A sequence of six sounds with two calibration pulses occuring within a 20-second period on the field tape can be analyzed on the WHOI system in about 46 minutes of computer time (5.75 minutes per sound) including plotting time. The break-down is as follows:

Step 2. Analog to Digital conversion, 40 seconds at ½ speed plus set-up time . . . . . . . . . . . . . . . . . . . . 2 minutes

Step 4. Plotting requires some experimentation to find the right places on the digital record, but only pertinent sequences are plotted . . . . . . (probably less than) 30 minutes

Step 6. The creation of a tape of eight data files for analysis: short bands of 4-channel data surrounding the two calibration pulses and prominent portions of each of the six sounds . . . . . 5 minutes

Steps 8 through 14. The sequential steps of analysis . . . . . . 8 minutes

Step 16. The location computation . . . . . . . . (less than) 1 minute

A longer sound sequence of six calibration pulses and 20 sounds within one minute on the field tape can be analyzed in a relatively shorter amount

of computer time (77 minutes), about 3.6 minutes per sound:

Step 2. A to D, 1 minute of field data at $\frac{1}{2}$ speed . . . . . . . 3 minutes

Step 4. Plot . . . . . . . . . . . . . . . . . . . . . . . 40 minutes

Step 6. File tape written . . . . . . . . . . . . . . . . . . 7 minutes

Steps 8 through 14. Analysis . . . . . . . . . . . . . . . . 26 minutes

Step 16. Location computation . . . . . . . . . . . . . . . . 1 minute

Direct analysis of individual sounds can be performed without an intermediate file tape (step 6), but requires about 5 minutes per sound for the analysis and location calculations (steps 8 through 16 only). The A to D and plot times (steps 2 through 4), if required separately, would more than double this. Because of the experimental nature of these analyses, the actual computer time per source location often has been two to three times the required times, yet in terms of the cost (currently about $110 per hour at WHOI), it has been the most economical way to reduce the acoustic array data.

Our method of analysis for sound source location requires accurate relative times for the signals. The easiest way we have found to assign these times has been through the plotting of the digital time series data. The plots have been the most time-consuming part of the analysis, but the advantages from this visual, accurate time record have seemed essential. The plotting program provides time ticks that mark each 0.01 sec, and allows the selection of precise bands around the signals for analysis. As a result, the uncertainty, and therefore the time required for the remainder of the analysis, is greatly reduced. Additionally, the plotting step provides the means for recognition of pertinent signals.

Computer analysis for location of underwater sound sources recorded on the four-hydrophone array has several advantages over previous systems of manual arrival-time-difference measurement. There is a considerable reduction in time of analysis, especially for longer series; therefore it is cheaper. There is greater accuracy, again especially over longer sequences. Even over long periods, successive analyses of the same sounds by computer are exactly alike — never true of manual measurements. And finally, potential operator bias in the analysis is mostly removed by relegating all of the measurements to the computer.

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| | Input | Function | Program | Output |
|---|---|---|---|---|
| 1. | Analog field tape | Select signals | Field data | Sounds to be analyzed |
| 2. | Analog data tape | Convert analog to digital | ADWW | Digital data tape |
| 3. | Digitized data | Select portions to plot | Indicate times | Data times on cards |
| 4. | Digital data tape | Plot 4 channels data | PTL4SIGNL | Plotted data sequences |
| 5. | 4 channel plot | Set up signal files | File size and times | File times on cards |
| 6. | Digital data tape | File tape written | WHALSIG | Tape of signal files |
| 7. | List of signal files | Choose files to be analyzed | Numbered files | Files to be analyzed |
| 8. | Tape of signal files | Filter to reduce noise | TIMSAN (NUFILT) | Files filtered |
| 9. | Tape of signal files | Locate signal in file | THRESHOLD | Signals found |
| 10. | Tape of signal files | Select signal segments | THRESHOLD | Segments for analysis |
| 11. | Tape of signal files | Fourier analysis | TIMSAN (COEFF) | Spectrum analysis |
| 12. | Tape of signal files | Power spectra computed | TIMSAN (FFAUSP) | Power spectra |
| 13. | Tape of signal files | Cross-correlation | TIMSAN (CCOR) | Relative times of signals |
| 14. | Tape of signal files | Times compared | LOCPREP | Arrival-time difference cards |
| 15. | Arrival-time differences | Calibration/location sequences | Selection of parameters | Sequence of time difference card |
| 16. | Time difference cards | Locations computed | WHALOC | Print-out of locations |

Table 1: Steps required for analysis of 4-hydrophone array data